Towards Quantitative First-Principles Models for Intrinsic Rotation in Axisymmetric Devices

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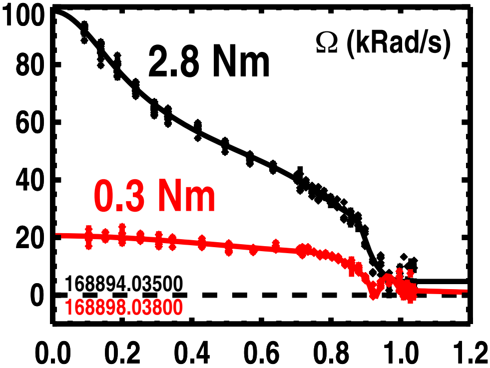
Outline

- Motivation and overview
  - Rotation peaking and nondiffusive momentum flux
- Edge rotation
  - Orbit-loss and transport-driven SOL flows
  - Simple kinetic-transport model and experimental tests
  - Open questions
- Core rotation
  - Complicated dependence on experimental parameters
  - Radially local: symmetry and symmetry-breaking
  - Radially global: simulations, results, and open questions

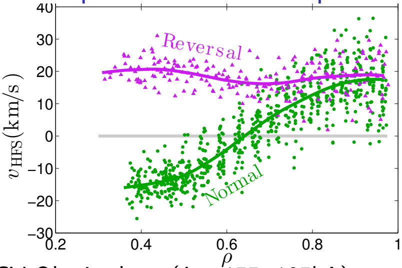
Motivation

- Future tokamaks will have relatively little applied torque (NBI$\rightarrow$fusion).
- Zero or low rotation can cause instabilities that make the plasma disrupt.
- Luckily, plasmas rotate without applied torque—"intrinsic rotation."
- We need to understand what determines intrinsic rotation profiles as part of identifying safe operating regimes for ITER or a future fusion plant.

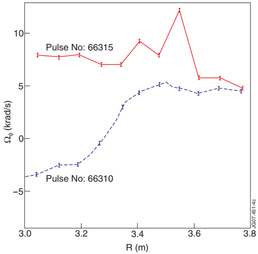
DIII-D, Grierson:



Tokamak plasmas rotate spontaneously without applied torque.



TCV Ohmic shots ($I_p \approx$155, 195kA)
Stoltzfus-Dueck PoP '15



JET ICRH shots ($I_p \approx$1.5, 2.6MA)
Eriksson PPCF '09

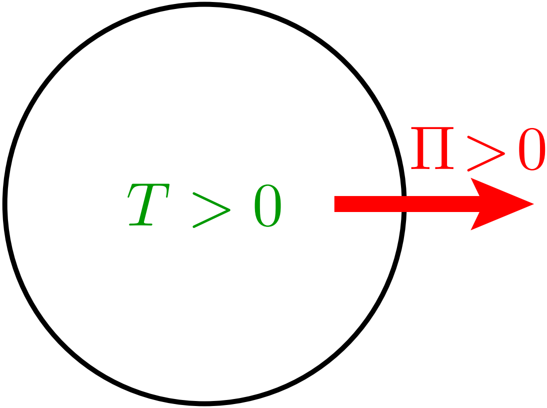
Typical intrinsic rotation profiles have three regions:

- Edge: Co-rotating and (roughly) understood
- Mid-radius "gradient region": Hollow or ~flat
  - Rotation often passes through zero at mid-radius. (Could be bad!)
  - Gradient exhibits sudden "reversals" at critical parameter values.
- Sawtoothing region inside $q = 1$: Flat or weak cocurrent peaking

In axisymmetric geometry, neoclassical momentum transport is negligible.

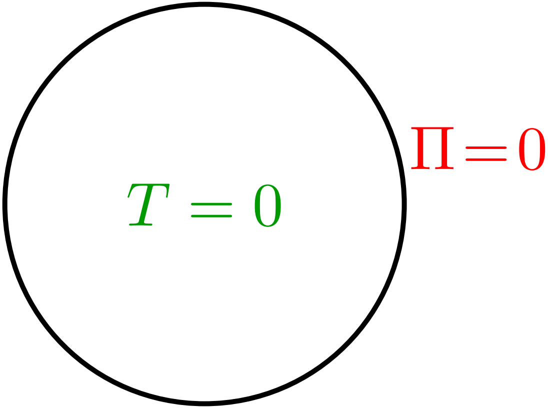
Rotation profiles are set by conservation of momentum.

$$T = \Pi = -\nu \nabla L \implies \nabla L = -T/\nu$$



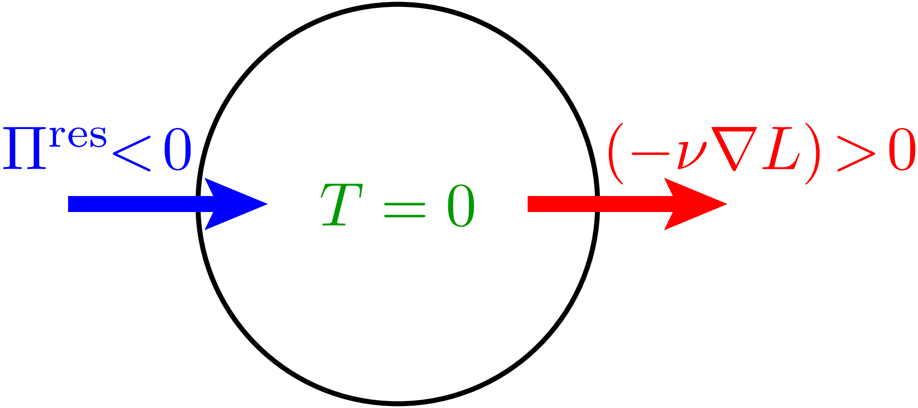
Rotation profiles are set by conservation of momentum.

$$0 = \Pi = -\nu \nabla L \implies \nabla L = 0/\nu$$



Rotation profiles are set by conservation of momentum.

$$0 = \Pi = -\nu \nabla L + \Pi^{\mathrm{res}} \Longrightarrow \nabla L = \Pi^{\mathrm{res}} / \nu$$



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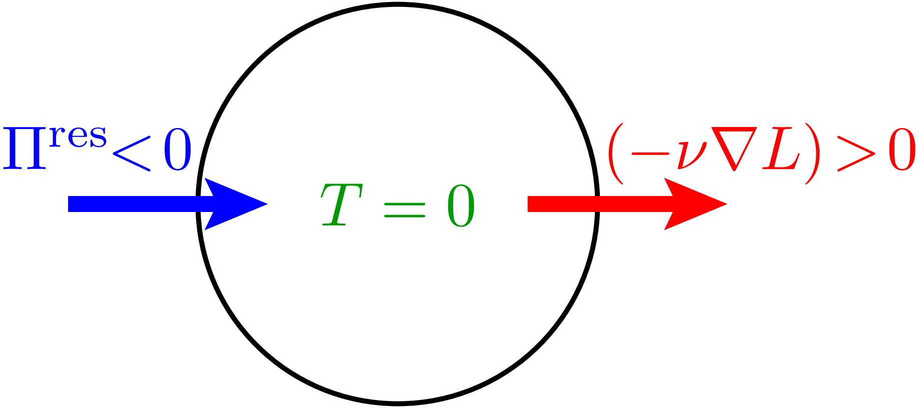
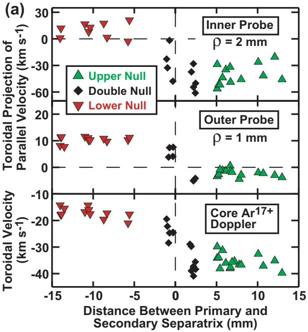
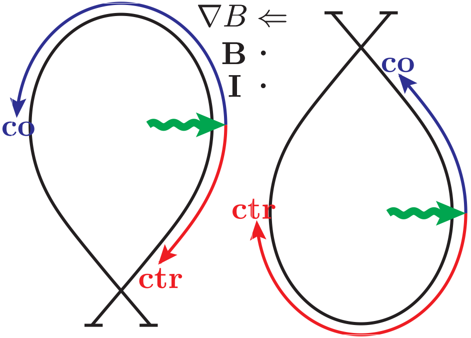


nontrivial intrinsic rotation ⇔ nondiffusive Π

C-Mod L-mode measurements suggest transport-driven flows.



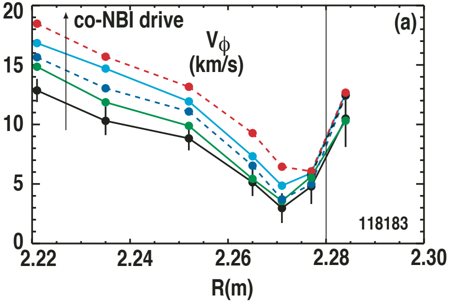
Mach probe in C-mod SOL
LaBombard PoP '04



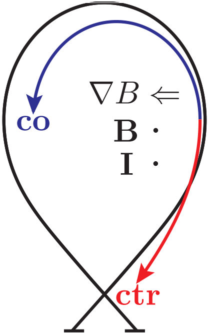
Schematic of transport-driven flows, showing topology dependence

L-mode toroidal rotation on C-mod : strong dependence on LSN vs USN.
Not only SOL rotation, but also in the core!
Motivated consideration of outboard-ballooning transport-driven flows.
This rotation shift (LSN vs USN) not observed in H-mode.

Co-current rotation at LCFS suggests ion orbit loss.



Co-current rotation "hump" near LCFS
deGrassie NF '09



Orbit excursions lead to co-current rotation at outboard midplane

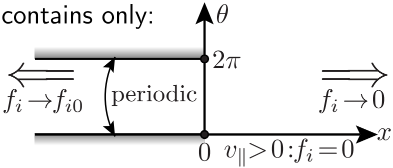
Co-current rotation feature ∼ubiquitous at outboard LCFS.
[Counter-current feature seen at inboard LCFS, Pütterich et al NF '12]
Suggests ion orbit excursions: "orbit loss", Pfirsch-Schlüter, etc.
But does this effect penetrate into the plasma?

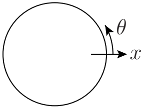
A simple kinetic transport theory for edge intrinsic rotation.

$$\partial_t f_i + v_{\parallel} \partial_\theta f_i - \delta v_{\parallel}^2 (\sin\theta)\, \partial_r f_i - \partial_r \left[D(r,\theta)\, \partial_r f_i \right] = 0$$

Extremely simple kinetic transport model contains only:

- Free flow along the magnetic field
- Radially-directed curvature drift
  - $\delta \doteq q\rho_i / L_\phi$
- Radial diffusion due to turbulence
  - Diffusivity D stronger outboard, decays in r
- Two-region geometry
  - Confined edge: periodic in θ
  - SOL: pure outflow to divertor legs





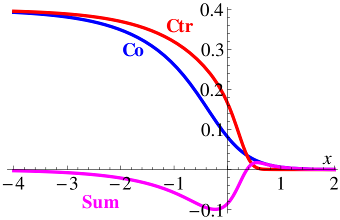
After some variable transforms, obtain steady-state equation

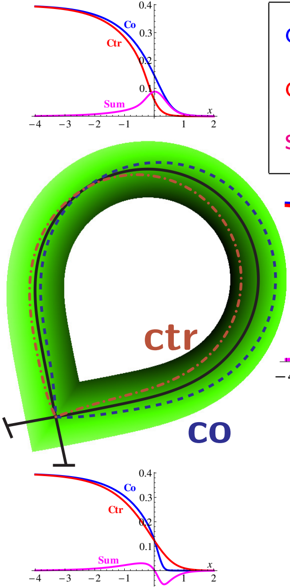
$$\partial_{\bar\theta} f_i = D_{\text{eff}}(v_{\parallel})\, \partial_{\bar r} \left(e^{-\bar r} \partial_{\bar r} f_i \right),$$

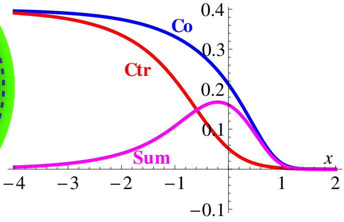
in which D_{eff} depends *on the sign* of $v_{\parallel}$. Stoltzfus-Dueck PRL '12

Model: ion drift orbits + spatially varying $D \Rightarrow$ edge intrinsic rotation

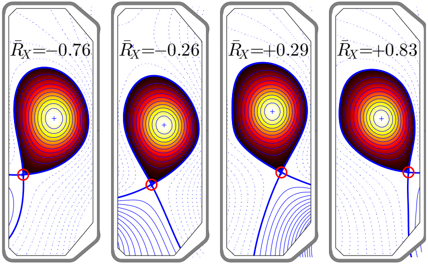
co	$\int_0^\infty \left\| v_\parallel \right\| f_i(v_\parallel) \mathrm{d}v_\parallel$
ctr	$\int_{-\infty}^0 \left\| v_\parallel \right\| f_i(v_\parallel) \mathrm{d}v_\parallel$
sum	$\int_{-\infty}^\infty v_\parallel \, f_i(v_\parallel) \mathrm{d}v_\parallel$

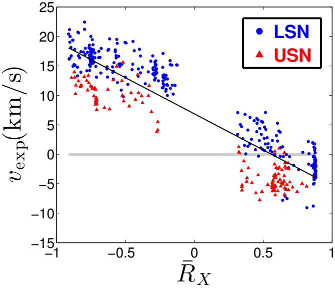






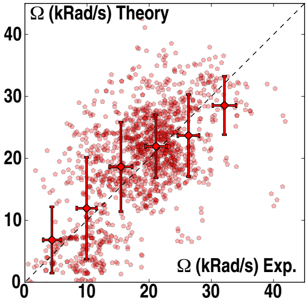
Tested model with dedicated scan and database analysis.





Concrete rotation prediction depends on $\bar{R}_X$.

- TCV: Ohmic L-mode, scan X-point position:
  - edge rotation shifts as expected.
- DIII-D: database over various L- and H-modes
  - had to account for NBI torque
- D↔C rotation shift is not small in the edge
  - Main-ion measurements are helpful.



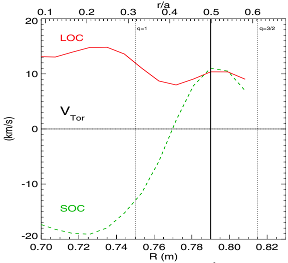
Top L and R: TCV, Stoltzfus-Dueck PRL '15
Bottom R: DIII-D L- and H-modes, Ashourvan APS '17

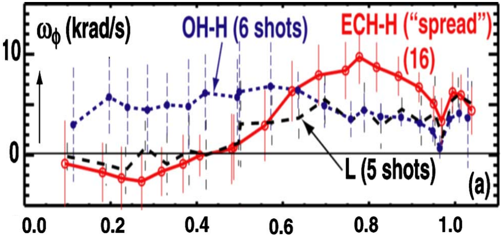
There are many open questions for edge intrinsic rotation.

The kinetic-transport model omits a lot of physics, including:

- Neutrals
  - possibly relevant for USN-LSN asymmetry in L-mode
  - some work on neutrals alone, but not much with neutrals and turbulence
- ELMs & MHD
  - Large ELMs sometimes appear to lock in outer edge
  - Active MHD affects rotation, was excluded from tests
- 3D fields
  - toroidally asymmetric **B** can exert a strong neoclassical torque
  - calculated with codes like GPEC and IPEC
  - but rotation prediction needs both 3D torque and turbulence
- Turbulent parallel acceleration (probably small, because $k_\parallel L_\perp \lll 1$)
- Trapping (maybe small, passing-ions carry most of the momentum)
- Collisions (relevant normalized collisionality actually *larger* on ITER)
- Radial currents in SOL (can exert $\boldsymbol{j} \times \boldsymbol{B}$ torque)

The core rotation gradient exhibits rich and varied behavior.





C-mod Ohmic L-modes ($n_e \approx 0.7, 0.8 \times 10^{20}\mathrm{m}^{-3}$)
Rice NF '13

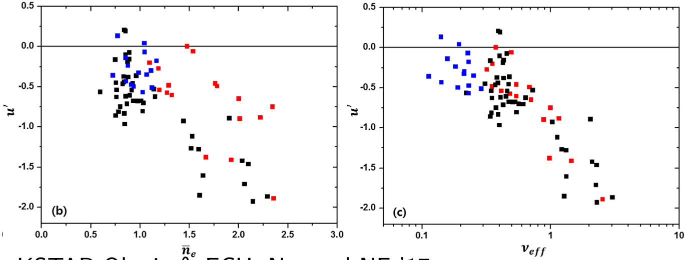
DIII-D L- & Ohmic & ECH H-modes
deGrassie PoP '07

A key quantity: normalized rotation gradient $u' = -(R/v_{ti})\partial_r v_\varphi$

- Usually either $u' \sim 0$ (flat) or $u' < 0$ (hollow) at mid-radius
- Complicated parameter dependence, many experimental observations
  - density or ν_{*e}: low↔flat, intermediate↔hollow, high↔flat
  - ECRH often causes hollow (AUG, DIII-D), but sometimes flat (KSTAR)
  - q profile: e.g. $u' < 0$ seen for $q < 3$ on KSTAR, $q < 3/2$ on C-mod

Candidates: ITG/TEM, ∇n_e, $\tilde{n}_e$, LOC/SOC, ITB

Many experiments find u' depends on electron collisionality.

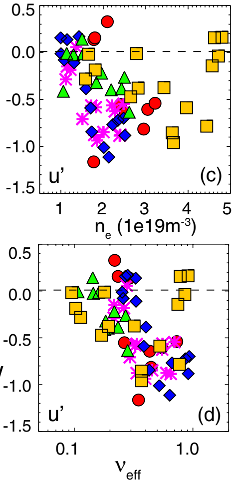


KSTAR Ohmic & ECH, Na et al NF '17

- TCV: critical n_e increases with T_e
- Standard reversal triggers (n_e, I_p, B_T) all affect ν_{*e}
- C-mod, KSTAR, AUG: $\nu_{*e} < \nu_{*e}^{\text{crit}}$:flat; $\nu_{*e} > \nu_{*e}^{\text{crit}}$:hollow
- But some AUG, KSTAR: flat again at higher $\nu_{\text{eff}} \propto \nu_e$

Physically, at least two distinct effects of ν_{*e}:

- affects trapped electrons, stabilizes collisionless TEMs
- if electron-heated: transfer energy to ions, $Q_i \Uparrow$



AUG Ohmic L-modes
McDermott NF '13

Many theoretical candidates, viewed through two frameworks.

In core orderings, many intrinsic rotation mechanisms are similarly sized.

- Unlike the edge, where $k_{\|} L_{\perp} \ll 1$ implies orbit-width-effects are largest.
- Challenging to differentiate between possible mechanisms.

Two dominant gyrokinetic frameworks to evaluate them:

- Radially local fluxtube ($\rho_* \ll 1$)
  - delta-f gyrokinetics expanded about a single flux tube
  - symmetry principle$\Rightarrow$most leading-order momentum-flux terms zero
  - other mechanisms do come in at higher order
  - easy to include or exclude specific effects
  - not naturally include profile curvature, intensity gradient,...
- Radially global
  - no symmetry principle (a plus and a minus)
  - automatically retains some terms that are higher-order in a fluxtube
  - naturally retains profile effects
  - full-F and delta-f versions, and subvariants
  - choices of radial boundary conditions and profile maintenance

Fluxtube: Symmetry restricts contributions to residual stress.

In the simplest radially local fluxtube limit with

- up-down symmetric magnetic geometry,
- no background rotation or rotation shear, and
- no background $\boldsymbol{E} \times \boldsymbol{B}$ shear,

the delta-f gyrokinetic equations satisfy a symmetry $[y \propto (\zeta - q\theta), s \propto \theta]$:

If $\quad f(x, y, s, v_\parallel, \mu, t),\ \phi(x, y, s, t) \quad$ is a solution
so is $\quad -f(-x, y, -s, -v_\parallel, \mu, t),\ -\phi(-x, y, -s, \varphi, t)$

with opposite sign of the dominant toroidal momentum flux.
(Peeters and Angioni PoP '05, Parra et al PoP '11)

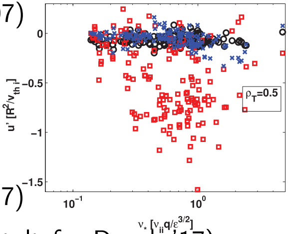
This implies: toroidal momentum flux should vanish for terms that flip sign, but does *not* imply that invariant terms *must* drive momentum flux.

What drives symmetry-breaking and momentum flux,
in the absence of rotation and of rotation shear?

Symmetry-breaking mechanisms in the fluxtube

Violate assumptions of symmetry argument:

- Background $\boldsymbol{E} \times \boldsymbol{B}$ shear (Dominguez and Staebler Phys. Fluids B '93)
- Pinch, $\Pi \propto v_\varphi$ (Peeters PRL '07, Hahm PoP '07)
- Up-down asymmetric $\boldsymbol{B}$ (Camenen PRL '09)



Higher-order terms, including mocked-up global:

- Intensity gradient (Gürcan PoP '10)
- Profile curvature (Camenen NF '11, Lu PoP '17)
- Geometrical corrections to drifts (Sung '13, Stoltzfus-Dueck '17)
- Corrections to fluxtube gyrokinetics (Parra and Barnes PPCF '15)
  - Neoclassical perturbation to turb mom transport (ν_{*i})
  - Turbulence inhomogeneity & finite orbit widths

Other Papers

- Reformulation in terms of wave momentum (Diamond PoP '08)

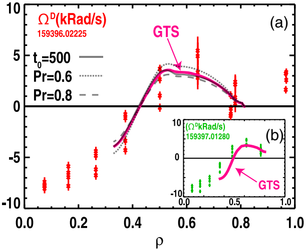
But predicted rotation gradients usually smaller than experimental levels.

e.g. figure, from Hornsby NF '17

Radially global delta-f simulations of momentum flux

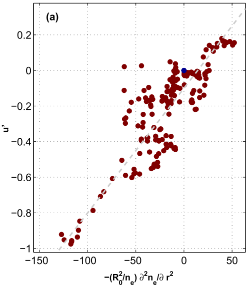
Delta-f, generalized with profile effects:

- Profile maintenance or relaxation?
- With or without neoclassical terms?
- Radial boundary conditions, usu Dirichlet
  - Typically get S-shaped rotation profiles



Rotation results:

- Can observe $\sim$large-enough rotation gradient
  - e.g. GTS$\leftrightarrow$DIII-D (top, Grierson PRL '17)
- from $\boldsymbol{E} \times \boldsymbol{B}$ shear, pinch, profiles (Waltz PoP '11)
- Role of magnetic shear (Wang PoP '10, Lu NF '15)
- Role of profile curvature (bot, Hornsby NF '18)
- Do the momentum fluxes scale linearly in small ρ_*?
  - Yes: GYRO, adiabatic-elec GKW
  - No: kinetic-electron GKW (but profile relaxation)



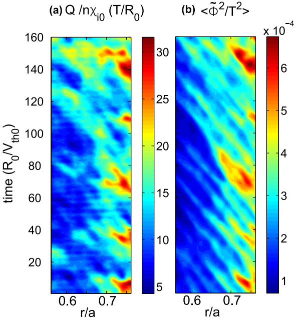
Radially global full-F simulations of momentum flux

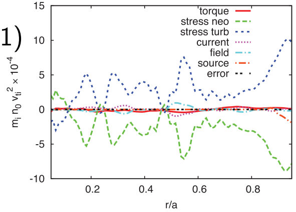
Full-F treatments:

- No symmetry principle, retain profile effects
- Source or profile relaxation? Usually source.
- Boundary conditions: usually toroidal annulus
- Expensive: usually run adiabatic-electron ITG
- Bursty or avalanche-like transport (Ku NF'12⇒)

Momentum observations

- Typically co-current rotation (e.g. Ku NF '12)
- Still RS from intensity gradient and $\boldsymbol{E} \times \boldsymbol{B}$ shear
- Barely-passing ions carry most of Π (Sarazin NF '11)
- Sometimes significant Π advected by curvature drift (Abiteboul PoP '11, Idomura PoP '14⇒)
- GT5D, hybrid electrons: Π flips sign ITG/TEM (Idomura PoP '17)





Summary

- Future tokamaks like ITER will run at low relative torque.
  - Need to avoid zero- or low-rotation regimes that can cause disruptions.
- Tokamaks rotate 'intrinsically'—without applied torque
  - Need a nondiffusive momentum flux to cause rotation gradient.
- Edge rotation: co-current, affected by SOL
  - Kinetic transport model (intensity gradient, orbit loss, SOL flows)
  - But many open topics (neutrals, radial SOL current,...)
- Core: flat or hollow, many contending models
  - measured ∇v_φ depends on many factors including ν_{*e}
  - Sudden transitions of ∇v_φ between negative and ~ 0: "reversals"
  - Fluxtube:
    - Symmetry argument restricts possibilities
    - Many models developed, predicted ∇v_φ a bit small
  - Global simulations
    - Unrestricted by symmetry argument
    - Varied observations, including experimentally relevant $|\nabla v_\varphi|$
- Much exciting work remains, including
  - more detailed and quantitative theory-expt, in core and edge
  - reconcile global and local results (e.g. Lu et al PoP '17)